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Low energy atmospheric neutrino flux calculation with accelerator-data-driven tuning

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We incorporated accelerator-data-driven tuning for hadronic interaction in our atmospheric neutrino flux calculation which has been used for the analysis of atmospheric neutrino oscillations at Super-Kamiokande. This new approach allows us to evaluate the flux uncertainty more directly compared to the conventional tuning using atmospheric muons. We tuned the hadronic interaction model in our calculation based on recent hadron production data measured by fixed-target accelerator experiments. The neutrino flux calculated with this new tuning is 5–10% smaller but still consistent with our previously published prediction within its uncertainty. The uncertainty associated with the new tuning was also evaluated based on the measurement errors of the accelerator data. Flux uncertainty was less than 9% in $0.2 < E_\nu < 10$ GeV/c region, which is an improvement over the conventional tuning. We performed the uncertainty evaluation in < 1 GeV/c region where the conventional tuning only provided the conservative uncertainty estimation.

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1. Introduction

A collision of a high energy cosmic-ray coming from extraterrestrial origins with Earth's atmosphere causes an air shower, *i.e.* a cascade of hadronic interactions. Consequently, neutrinos are produced through decays of pions and kaons in the air shower. Such "atmospheric neutrinos" have wide ranges of energy (100MeV–O(PeV)) and flight length (10–$O(10^4)$ km), and are promising signals for several physics including neutrino oscillation.

To study for atmospheric neutrinos, the prediction of its flux are necessary. In Super-Kamiokande experiment [1], the neutrino flux is calculated by using a 3D Monte Carlo simulation (MC) for air showers developed by *Honda et. al.* [4], which is often called "Honda flux".

The dominant uncertainty of Honda flux arises from the hadronic interaction in the air shower. *Honda et. al.* [5] tuned hadronic interaction model in their MC based on atmospheric μ flux observations [6]. This "μ tuning" suppresses the flux uncertainty down to ~7% in $1 < E_\nu < 10$ GeV region as shown in Fig.11 in [7]. Still, there is relatively large uncertainty in $E_\nu < 1$ GeV and in $E_\nu > 10$ GeV.

In this article, we tuned the Honda-flux MC based on data measured in accelerator experiments. Several accelerator experiments for precise measurement of hadronic production has been conducted/planned. Such data complements the μ tuning by covering different phase space from μ observations. We focus on the low energy neutrinos from O(0.1 GeV) to O(10 GeV). Such low energy region is important for the neutrino oscillation study in Super-Kamiokande [1] and Hyper-Kamiokande [2]. It is also important for DSNB searches [3] where the atmospheric neutrinos can be the main backgrounds.

2. Accelerator-data-driven tuning

For the tuning, we used several fixed-target accelerator data: HARP [8, 9], BNL E910 [10], NA61 [11], NA49 [12], NA56/SPY and NA20 [13]. These experiments use a proton beam whose momentum ranges from 3 to 450 GeV/c, and provide inclusive differential cross-sections of $\pi^\pm, K^\pm$, and/or proton productions, as summarized in Table 1. The notation of the differential cross-section varies depending on the experiments; some use $\frac{d^2\sigma}{dpd\theta}$, others use $\frac{d^2\sigma}{dpd\Omega}$, $\frac{d^2\sigma}{dx_F dp_T}$, etc. Hereafter we use an invariant form $E\frac{d^3\sigma}{dp^3}$ to unify the notation.

In the MC, the rate of hadron production interaction between cosmic-rays and air nucleus is determined by the air density modeled by NRMSISE-00 and the total production cross section σ_{prod}. Then, the number, momentum magnitude, and direction of produced particles are determined according to the number density $E\frac{d^3n}{dp^3}$. The $E\frac{d^3n}{dp^3}$ depends on the incident particle type, the incident particle's momentum magnitude, and the produced particle type. The $E\frac{d^3n}{dp^3}$ distributions used in our MC are calculated from JAM model [14] for interactions with the incident particle energy less than ~31.6 GeV/c^2 and DPMJET-III model for higher energies. The σ_{prod} and $E\frac{d^3n}{dp^3}$ are related to $E\frac{d^3\sigma}{dp^3}$ as:

$$E\frac{d^3\sigma}{dp^3} = \sigma_{prod} E\frac{d^3n}{dp^3}. \quad (1)$$

Table 1: List of accelerator data used in this analysis. These data provide the differential cross-section for the interaction $p + A \to x_{out} + X$. Types of target atoms and the reference number are shown in each cell.

	Beam momentum [GeV/c]					
x_{out}	3	5	6.4	8	12	12.3
$\pi^{\pm}$	Be, C, Al [8]	Be, C, Al [8]	Be [10]	Be, C, Al [8]	Be, C, Al [8]	Be [10]
$K^{\pm}$	–	–	–	–	–	–
p	Be, C, Al [9]	Be, C, Al [9]	–	Be, C, Al [9]	Be, C, Al [9]	–

	Beam momentum [GeV/c]				
x_{out}	17.5	31	158	400	450
$\pi^{\pm}$	Be [10]	C [11]	C [12]	Be [13]	Be [13]
$K^{\pm}$	–	C [11]	–	Be [13]	Be [13]
p	–	C [11]	C [12]	Be [13]	Be [13]

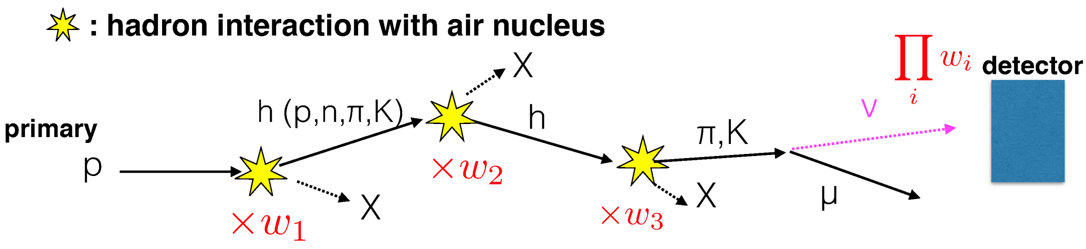

Figure 1: Schematic view of chain interactions associated with neutrino production.

In the accelerator-data-driven tuning, we defined a *weight* to correct the difference between data and MC, as:

$$w \equiv \left(E\frac{d^3\sigma}{dp^3}\right)_{data} / (\sigma_{prod})_{MC} \left(E\frac{d^3 n}{dp^3}\right)_{MC}, \tag{2}$$

where the subscripts *data* and *MC* represent the expected values from the measured data and the MC, respectively. We prepared tables of weight w for each produced-particle type (π^+, π^-, K^+, K^-, p, n) and for various incident momenta from 3 to 1000 GeV/c. The details of weight derivation was written in [16].

In the air-shower MC, neutrinos are produced at the end of a chain of hadron interactions like Fig. 1. We applied the w to each hadronic vertex on the interaction chain. The product $W_{event} \equiv \prod_i w_i$ was used as an event weight when counting the number of neutrinos hitting the detector, where w_i represents the weight applied to the i-th vertex on the chain.

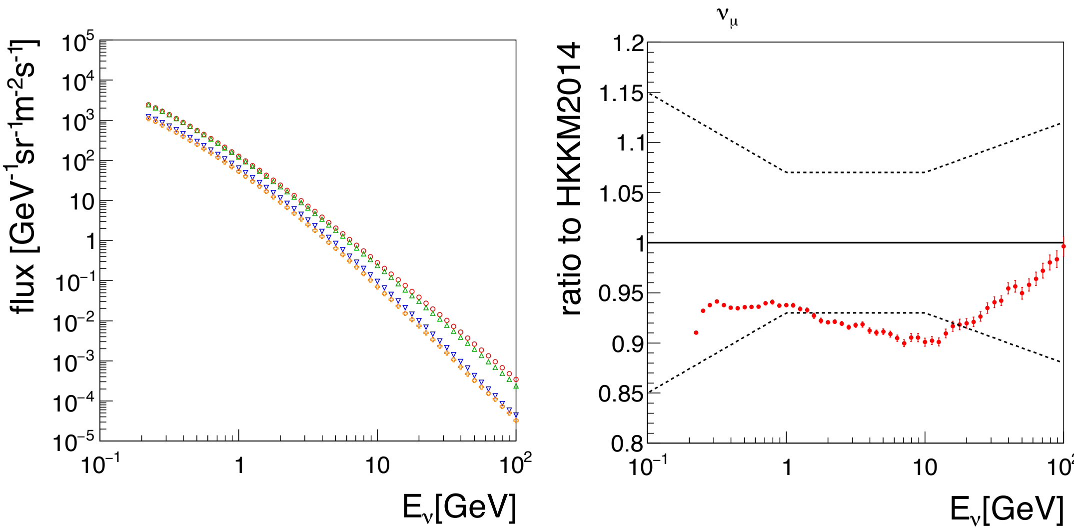

Figure 2: (a) Flux predictions with the accelerator tuning of ν_μ (red ◯), $\bar{\nu}_\mu$ (green △), ν_e (blue ▽), and $\bar{\nu}_e$ (orange +). Their error bars shows MC statistical error only. (b) Ratio to the original flux prediction [4]. The red dots corresponds to ν_μ flux. Dashed line shows the systematic uncertainty reported in [7].

3. Flux prediction with the tuning

We simulated the neutrino flux with applying the weight in Eq. (2). The result is shown in Fig. 2 (a). The flux is almost consistent with the one previously reported in Ref. [4] considering its systematic error, though it has a tendency to be ∼5–10% smaller. The predictions of flavor ratio, $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$, and neutrino-antineutrino ratios ,$\bar{\nu}_\mu/\nu_\mu$ and $\bar{\nu}_e/\nu_e$, were also calculated with the accelerator tuning, as shown in Fig. 3. The new tuning method did not have a significant impact for these predictions.

4. Flux uncertainty

The flux uncertainty associated with the accelerator tuning was evaluated based on the measurement uncertainties of the fixed-target data. When proper data for the uncertainty estimation were not available, we instead used a DPMJET-III [15] implemented in CRMC [17]. We considered several uncertainty sources, which is shown in Fig. 4 as a function of neutrino energy E_ν. The total flux uncertainty was evaluated to be 7–9% in $E_\nu < 1$ GeV region. In that region, the conventional muon tuning only provided the conservative uncertainty estimation. Up to 10 GeV E_ν, the accelerator-data-driven tuning put reasonable and smaller uncertainty compared to the conventional muon tuning. The largest uncertainty below ∼10 GeV came from the error-bar sizes of the $\frac{d^2\sigma}{dpd\theta}$ in the fixed-target data ("◯" in Fig. 4). In this energy region the HARP and BNL E910 data (p_{beam} = 3–17.5 GeV/c) were mainly used for the tuning. In higher energy region, such uncertainty was suppressed due to the precise measurements provided by NA61 and NA49 (p_{beam} = 31 and 158 GeV/c). The normalization uncertainty of the accelerator data ("×" in Fig. 4) significantly contributes above ∼10 GeV, mainly because the overall scales of NA20 and NA56/SPY data (p_{beam} = 400 and 450 GeV/c) have relatively large uncertainties. At sub-GeV region, a limited phase space coverage of the

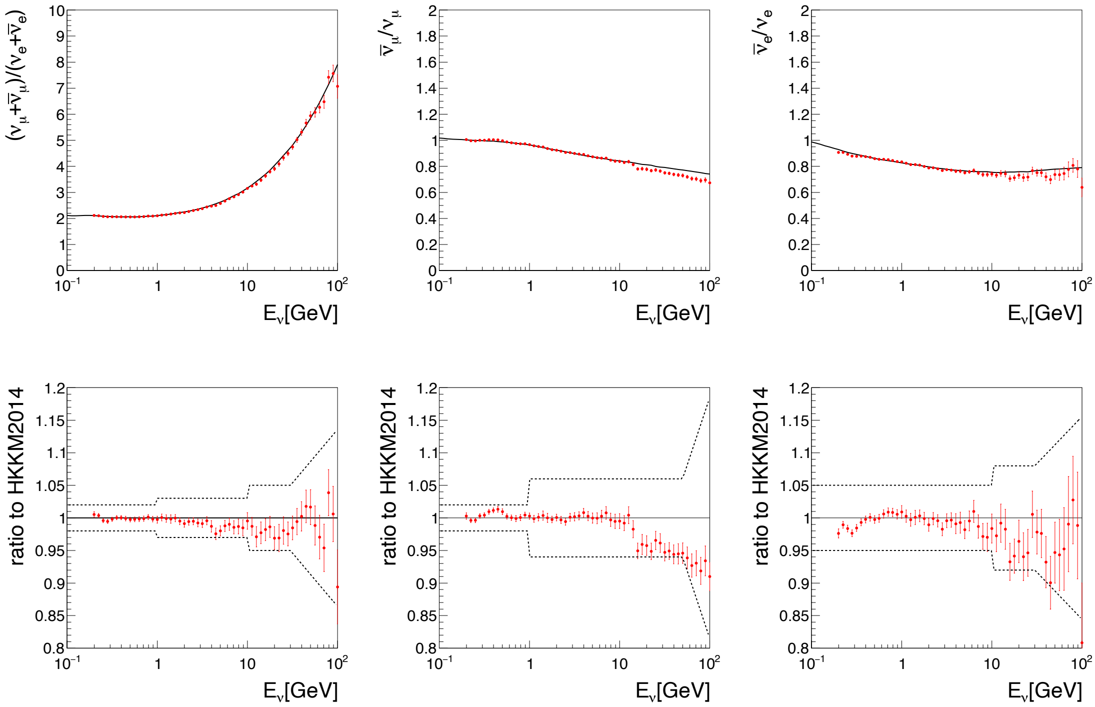

Figure 3: Flux ratio predictions with accelerator tuning. On the top panel, flavor ratio (left), $\bar{\nu}_\mu/\nu_\mu$ ratio (middle), and $\bar{\nu}_e/\nu_e$ ratio (right) are shown. The red dots show our accelerator tuning predictions, while the black line is the original predictions [4]. On bottom panel, the ratio of the accelerator tuning to the muon tuning are shown. The dashed lines are uncertainties of flux ratios used in Super-Kamiokande analysis.

accelerator data on x_F-p_T plane ("△" in Fig. 4) is a large uncertainty source. These uncertainties will be able to reduce with more-precise and wider-phase-space measurements with low energy beam (< 10 GeV/c), which will be provided by the future accelerator experiments. We focused on the low energy region up to O(10 GeV) E_ν in this study and used the fixed target data up to 450 GeV/c beam momentum for the tuning. Above that energy region hadron interactions caused by O(1 TeV/c) particles largely contribute to neutrino production, that arises the uncertainty in high energy which is shown in "+" in Fig. 4.

5. Summary

We tuned the Honda flux MC based on the fixed-target data with 3–450 GeV/c beam momentum. The neutrino flux prediction with this new tuning was modified ~10% smaller than the original flux, but still consistent within the unceratinty. The flux ratios, $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$, and $\bar{\nu}_\mu/\nu_\mu$ and $\bar{\nu}_e/\nu_e$, are well consistent with the original ones. The uncertainty related to the tuning was evaluated based on the uncertainties of the fixed-target data. We provided quantitative uncertainty of 7-9% in $E_\nu < 1$ GeV region, where the original muon tuning only provided a conservative estimation. Dominant uncertainties arise from the measurement errors and the limited phase space coverage of the fixed target data. We expect these uncertainties will be improved with new data from the future fixed-target experiments.

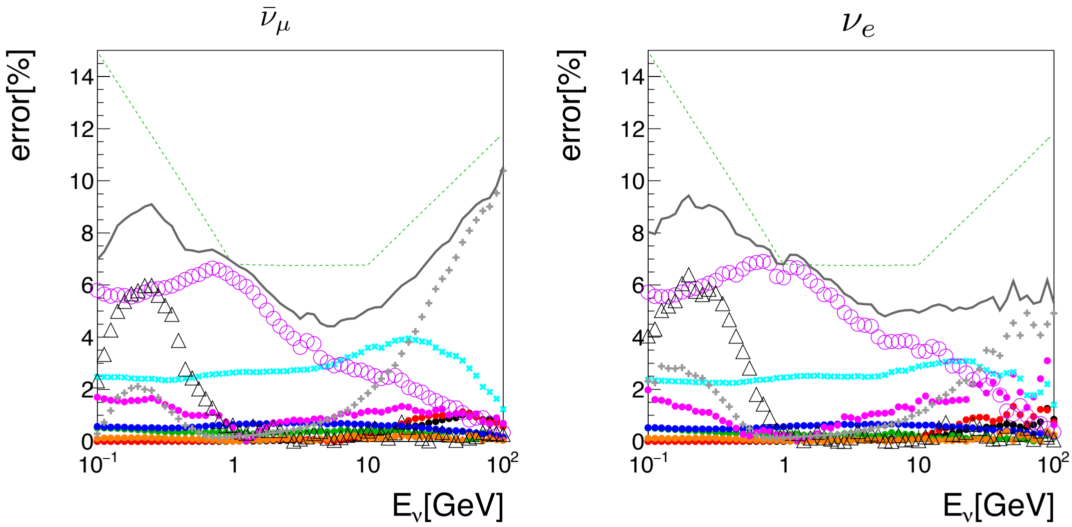

Figure 4: Systematic uncertianties in the accelerator tuning for $\bar{\nu}_\mu$ flux (right) and ν_e flux (left). The solid line shows the total systematic uncertainty. The markers show the uncertainty came from each uncertainty source: measurement error of accelerator data (violet ◯), normalization uncertainty of accelerator data (cyan ×), contribution from x_F-p_T regions not covered by accelerator data (black △), contribution from energy regions not covered by accelerator data (gray +), and others (dots). For comparison, the uncertainty evaluated from the muon tuning [7] is shown in the dashed line.

The combined analysis of the accelerator-data-driven tuning and the conventional tuning using the atmospheric muon will further reduce the uncertainty, that is a topic for future study.

References

[1] S. Fukuda *et. al.* (Super-Kamiokande), Nucl. Instrum. Meth. A501 (2003) 418.

[2] K. Abe *et. al.* (Hyper-Kamiokande), https://arxiv.org/abs/1805.04163 (2018).

[3] K. Abe *et. al.* (Super-Kamiokande) Phys. Rev. D 104, 122002 (2021).

[4] M. Honda *et. al.*, Phys. Rev. D 92, 023004 (2015).

[5] T. Sanuki *et. al.*, Phys. Rev. D 75, 043005 (2007).

[6] S. Haino et al. (BESS), Phys. Lett. B594, 35 (2004). T. Sanuki et al., Phys. Lett. B541 234 (2002); Erratum B581 272 (2004). K. Abe et al. (BESS), Phys. Lett. B564, 8 (2003).

[7] M. Honda *et. al.*, Phys. Rev. D 75, 043006 (2007).

[8] M. Apollonio et al. (HARP), Phys. Rev. C 80, 035208 (2009). M. G. Catanesi et al. (HARP), Phys. Rev. C 77, 055207 (2008).

[9] M. Apollonio et al. (HARP), Phys. Rev. C 82, 045208 (2010)

[10] I. Chemakin *et. al.* (E910), Phys. Rev. C 77, 015209 (2008); Erratum C 77, 049903 (2008).

[11] N. Abgrall et. al. (NA61/SHINE), Eur. Phys. J. C 76, 84 (2016).

[12] C. Alt et. al. (NA49), Eur. Phys. J. C 49, 897 (2007).

[13] M. Bonesini et.al., Eur. Phys. J. C 20, 13 (2001).

[14] K. Niita et al., Radiat. Meas. 41, 1080 (2006)

[15] S. Roesler, R. Engel, and J. Ranft (2000), hep-ph/0012252.

[16] K.Sato, Proceedings, 37th International Cosmic Ray Conference (ICRC 2021), PoS(ICRC2021)1210.

[17] R. Ulrich, T. Pierog, C. Baus. "The Cosmic Ray Monte Carlo Package, CRMC (v2.0.1)". Zenodo (2021). https://doi.org/10.5281/zenodo.4558705